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Selected parameters of the combustion process in a compression-ignition engine at different angles of the beginning of injection of mixtures of rapeseed oil with n-hexane

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The article presents the results of experiments in which a compression-ignition engine was fueled with a mixture of rapeseed oil with a 10% addition of n-hexane. The effect of changing the fuel injection start angle on selected indicators of the combustion process was evaluated. The tests were conducted at a fixed vehicle speed of 90 km/h. The addition of n-hexane made it possible to improve the characteristics of the combustion process of rapeseed oil. The maximum combustion pressure increased to 9.5 MPa (DF: 9.66 MPa; RO: 8.71 MPa), and the ignition delay was shortened. Advancing the pilot injection by –6°CA resulted in stabilization of the kinetic combustion phase; in reality, due to map interpolations and auto-adaptation strategies of the controller, the offset was approx. –4°CA, indicating that it must be taken into account in the interpretation of the results. The average indexed pressure reached 0.805 MPa (DF: 0.813 MPa; RO: 0.728 MPa), and the maximum pressure build-up rate (dp/dα) reached 0.375 MPa/°CA, approaching the 0.399 MPa/°CA recorded for DF. The rate of heat release was in the range of 86–93 kJ/m³·°CA, clearly lower than that of RO (130 kJ/m³·°CA). The results confirm that appropriate modification of the fuel composition, together with a properly selected injection angle, allows compression-ignition engines to burn renewable fuels. The results of the measurements were described with regression relationships, which allows their use in further simulation and development work.

Key words: *alternative fuels, injection angle, diesel engine, indication, rapeseed oil*

1. Introduction

In recent decades, alternative fuels for compression-ignition engines have gained importance in both urban public transport and passenger vehicles. Road and chassis-dynamometer studies consistently demonstrate that conditioning of both conventional and alternative fuels can improve combustion quality and reduce particulate and smoke emissions, as confirmed in full-scale tests on passenger cars and buses [4–6]. This trend responds to environmental imperatives, rising fossil-fuel prices, and the pursuit of greater energy independence. To successfully deploy plant-derived fuels such as rapeseed oil, a comprehensive understanding of combustion processes in electronically controlled diesel injection systems is essential.

This paper addresses the practical use of rapeseed oil enriched with n-hexane in compression-ignition engines. Numerous studies [15–17] have shown that the effectiveness of such a solution depends primarily on the proper modification of the injection system – in particular, on the selection of the injection timing. The high viscosity and surface tension of rapeseed oil cause deterioration of atomization, prolonged injection duration, and delayed auto-ignition [2, 3, 11]. The introduction of a 10% volume share of n-hexane – as proven in studies [8], reduces the viscosity by more than 50%, lowers the density and surface tension of the mixture, bringing its physicochemical properties closer to diesel fuel. Several benefits of this modification have been observed. First, the reduction in flow resistance allows the fuel system to maintain nominal pressures, which prevents overloading the high-pressure pump [12]. Second, the improved atomization and faster evaporation of the n-hexane fraction promote homogeneous formation of the fuel-air mixture, resulting in an 8–12% increase in average indexed pressure in the 2000–3000 rpm speed range [13]. Third, n-hexane dissolves deposits accumulating in the injector needle zone, reducing their build-up and prolonging the nozzle's trouble-free period [14]. Road tests also eliminated the phenomenon of impeded hot start, observed with RO (rapeseed oil) – only fuelling [10].

However, the limitations of the solution in question cannot be overlooked. The lower cetane number of the mixture (a decrease of 3–5 relative to DF) prolongs the ignition delay phase; at nominal injection settings, this results in a shift of the maximum combustion pressure beyond the optimal angular range, which lowers the indexed efficiency and raises the exhaust gas temperature [3]. A prerequisite for using a mixture of canola oil with 10% n-hexane is the adaptation of the injection strategy. A compilation of research results [7, 9] allows us to formulate two key conclusions, i.e., that the addition of 10% n-hexane significantly improves the physicochemical properties of RO, bringing viscosity, density and surface tension closer to levels acceptable for reservoir injection systems. That efficient combustion requires accelerating the onset of injection.

The purpose of the following discussion, therefore, is a preliminary analysis of how to select the injection angle for an engine fueled by rapeseed oil-based fuel blended with 10% n-hexane, and to assess the impact of these changes on the combustion process.

2. Materials and methods

2.1. Tests stand

The object of the study was a compression-ignition engine with a bunker injection system, which was built into in a Fiat Qubo vehicle. The vehicle's engine met the EURO 5 exhaust gas standard. The data and technical parameters of the test engine are given in Table 1.

Table 1. Main characteristics of the Fiat Qubo vehicle used for the tests

Parameter	Unit
Engine displacement	1248 cm³
Cylinder bore	69.6 mm
Piston stroke	82 mm
Compression ratio	16.8:1
Maximum power	55 kW/75 HP
Maximum torque	190 Nm
Idle speed	850 ±20 rpm
Engine speed at maximum torque	1500 rpm
Fuel injection / supply system	Common rail system
Exhaust aftertreatment systems	Exhaust gas recirculation (EGR), particulate filter

The test stand is shown in a block diagram (Fig. 1). The test vehicle could be fueled with diesel fuel from the vehicle's main tank and other liquid fuel mixtures from an installed auxiliary tank, which allowed quick replacement of the test fuel. The entire process was managed by the engine controller (ECU1 – Electronic Control Unit 1). Fuel consumption was measured using a flow meter, which took into account the return overflow from the injectors and high-pressure pump. Fuel was then fed sequentially to the high-pressure pump, the fuel tank and the injectors. The control and measurement track allowed recording the engine's operating parameters under dynamic conditions, measuring fuel consumption and environmental and energy parameters. The AVL IndiMicro 602 measurement system allowed the recording of rapidly varying in-cylinder pressures and the analysis of injection parameters. Other actual values of engine operation were recorded using the Multiecuscan OBD II (On Board Diagnostics) diagnostic interface.

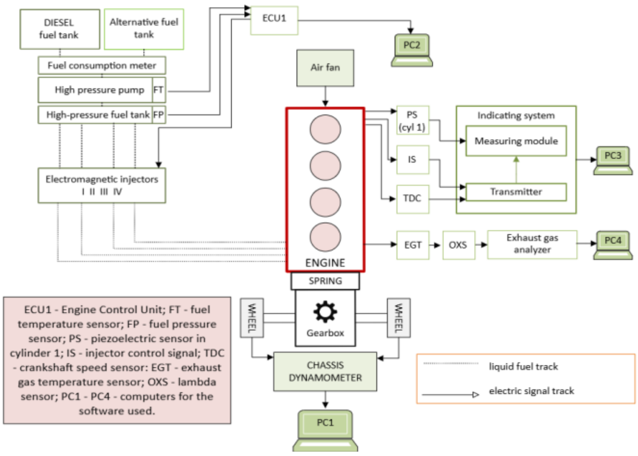

Fig. 1. Block diagram of the test bench

2.2. Course of tests

As part of the preliminary tests, the test vehicle was subjected to simulated tests on a chassis dynamometer according to the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) [1]. Measurement points were selected, i.e., driving at a constant speed of 90 km/h. During the tests performed, the engine was operated with the load resulting from the resistance to motion (rolling resistance, air resistance) mapped on the chassis dynamometer set in "driving simulation" mode. Three fuels were selected to power the engine with nominal software in the controller, which were assigned designations used consistently throughout the rest of the article: "DF" – diesel fuel as a reference (reference) test; "RO 90%Hex10%" – rapeseed oil with the addition of 10% n-hexane; "RO" – rapeseed oil.

2.3 Modification of the start time of the first pre-injection

The different viscosity, density and flash point of the canola oil-n-hexane mixture compared to diesel [14] necessitate the modification of the injection start angle, among other things. As a reference test, power and torque measurements were carried out on a chassis dynamometer, feeding the engine with diesel at nominal engine controller settings. In order to select the angle of first pilot injection for the RO 90%Hex10% mixture, ten tests were carried out in which each time the angle of first pilot injection was delayed by "–1°CA" from the measured nominal value of "–32°CA". It was noted that at the value of delaying the first pilot injection by "–6°CA", the parameters measured on the chassis dynamometer were the closest with respect to the measurement when the engine was fed with diesel fuel with nominal engine controller software. On this basis, the angle of the first pilot injection of "–38°CA" was selected (Fig. 2). It was assigned the following designation used consistently hereafter: "Pilot(–6°)RO 90%Hex10%" – canola oil with the addition of 10% n-hexane, with the first pilot injection adjusted by –6°CA.

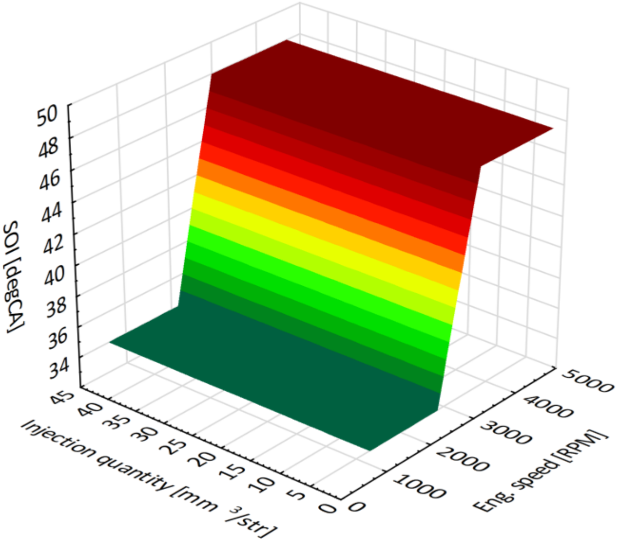

Fig. 2. Modified control map of the angle of the first pilot injection [˚CA] depending on the injection rate [mm^3/cycle] and engine crankshaft speed [rpm]

3. Results

Figures 3 to 6 show the course of cylinder pressure, the rate of heat release, and the signal controlling the opening of the injectors as a function of the engine's crankshaft rotation when fed successively with diesel, canola oil, canola oil with 10% n-hexane addition, and canola oil with 10% n-hexane addition with the first pilot injection adjusted by

–6°CA, while running on a chassis dynamometer at 90 km/h.

In Figure 3, at $\alpha_{inj} \approx -12$°CA for diesel fuel, the cylinder pressure rises to about 8.98 MPa, and the maxima of heat release and pressure appear near TDC, indicating a short ignition delay time and a rapid combustion phase. On the other hand, the use of rapeseed oil (Fig. 4) at an injection angle $\alpha_{inj} \approx -2$°CA, affects the pressure maximum, which was 8.71 MPa near $\alpha_{Pc,max} \approx 11$°CA. Adding 10% n-hexane (Fig. 5) allowed to reach $P_{(c,max)} \approx 8.38$ MPa at $\alpha_{Pc,max} \approx 11.7$°CA – lower than with diesel fuel. Analyzing the dQ/dα characteristics, it was noted that this fuel ignites significantly faster than pure rapeseed oil. Figure 6, shows the results obtained for canola oil feed with 10% n-hexane, where shifting the injection angle by "–6°CA" earlier relative to the nominal control, led to a significant increase in maximum pressure (up to 9.47 MPa) and reaching its maximum at an angle $\alpha_{Pc,max} \approx 11.7$°CA. The previously introduced pilot dose shortened the ignition delay time of the main fuel dose, resulting in a more rapid combustion just after TDC. Delaying (or appropriately "phase-shifting") the pilot injection can reduce surges at less stressed operating points. It is noteworthy that although the control system was set to shift the pilot injection angle by –6°CA relative to the nominal map, the recording of measurements at 90 km/h did not achieve exactly this change. This is because the engine controller uses a series of interpolations based on values from neighboring cells of the injection map and additionally applies auto adaptive strategies (e.g., as a function of speed, fuel dose or exhaust gas temperature). In the tests in question, instead of the expected –6°CA, the real value of the pilot injection offset averaged about –4°CA relative to the reference value, as can be seen from the actual angles recorded in the charts. On the one hand, this illustrates the flexibility and adaptability to current operating conditions, on the other hand, it shows that the nominally introduced correction does not always translate linearly into an identical angle change in the actual engine cycle, so the interpretation of the results should always take into account the specifics of the controller and its operation under the dynamic conditions of actual operation.

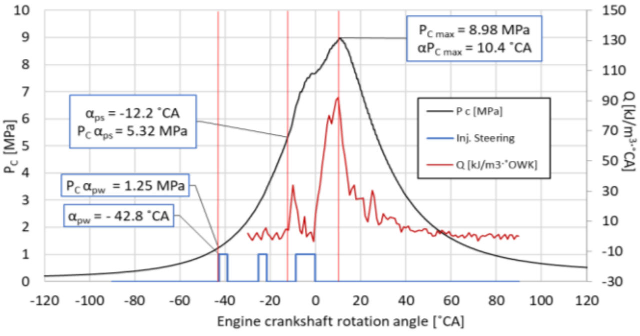

Fig. 3. The course of cylinder pressure, heat release rate, and injector opening control signal as a function of engine crankshaft rotation when fed with diesel fuel while running on a chassis dynamometer at 90 km/h

Figures 7 through 12 show the recorded average index pressure, a box plot of average index pressure from 70 measurement cycles, maximum combustion pressure, maximum rate of combustion pressure build-up, average fuel burn rate, and maximum heat release rate when fed successively with diesel fuel, canola oil, canola oil with 10% n-hexane addition, and canola oil with 10% n-hexane addition with the first pilot injection adjusted by –6°CA, while running on a chassis dynamometer at 90 km/h.

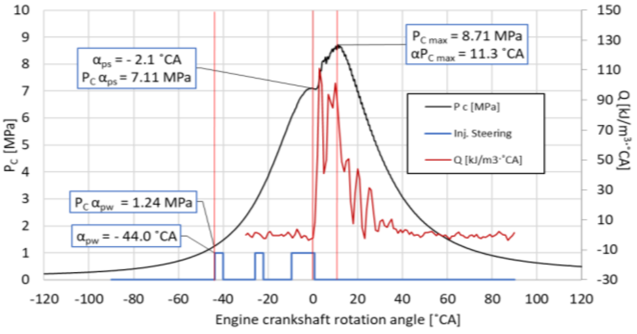

Fig. 4. The course of the cylinder pressure, the rate of heat release, and the signal controlling the opening of the injectors as a function of the engine's crankshaft rotation when fed with rapeseed oil while running on a chassis dynamometer at 90 km/h

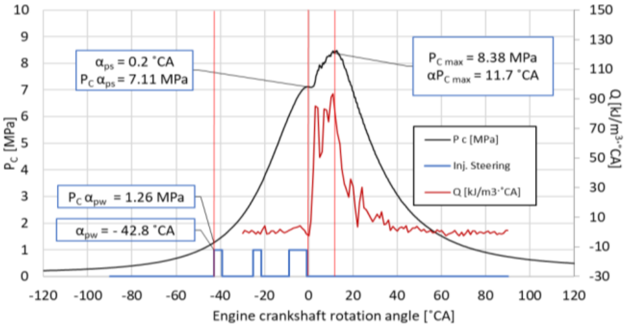

Fig. 5. The course of the cylinder pressure, the rate of heat release, and the signal controlling the opening of the injectors as a function of the engine's crankshaft rotation when fed with canola oil with the addition of 10% n-hexane, while running on a chassis dynamometer at 90 km/h

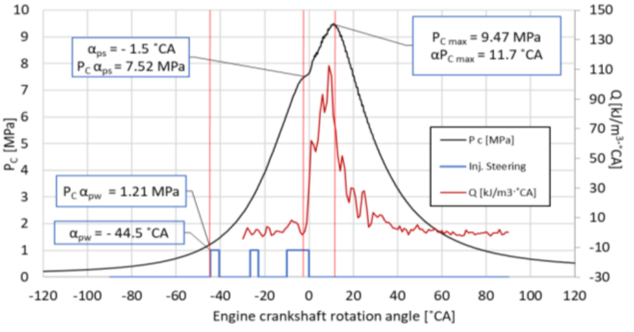

Fig. 6. The course of cylinder pressure, heat release rate, injector opening control signal as a function of engine crankshaft rotation when feeding with canola oil with 10% n-hexane with the first pilot injection adjusted by –6˚CA, while driving on a chassis dynamometer at 90 km/h

The value of the average indexed pressure for DF was 0.816 MPa. For the 70 cycles analyzed, it was characterized by a narrow distribution and high consistency of individual measurements, indicating their stability. The value of the maximum combustion pressure, recorded during diesel fuel tests, was 9.58 MPa. The maximum pressure build-up rate (dp/dα) for DF was 0.399 MPa/°CA. The amount of fuel burned, was 966.9 kJ/m³. The maximum rate of heat release was 90.4 kJ/m³·°CA.

When fed with canola oil, the value of the average indexed pressure reached 0.805 MPa. For 70 engine cycles, this parameter reached the lowest value among all fuels. The maximum combustion pressure was 10.58 MPa. The maximum pressure build-up rate (dp/dα), for canola oil reached 0.540 MPa/°CA. The average burn rate was 1084.3 kJ/m³. The recorded maximum rate of heat release was 130.0 kJ/m³·°CA.

When fed with rapeseed oil with 10% n-hexane addition, the value of the average indexed pressure was 0.728 MPa. The value of the average pressure was the smallest among all the fuels tested for the 70 cycles analyzed and had the least variability. Such a result may be due to the variability of the combustion process in the presence of a small addition of n-hexane. The maximum combustion pressure was 9.00 MPa. The maximum pressure build-up rate (dp/dα) was 0.417 MPa/°CA. The value of the average burn rate for RO 90%Hex10% was 910.9 kJ/m³. As for the maximum rate of heat release – for the RO 90%Hex10% mixture it was 92.6 kJ/m³·°CA.

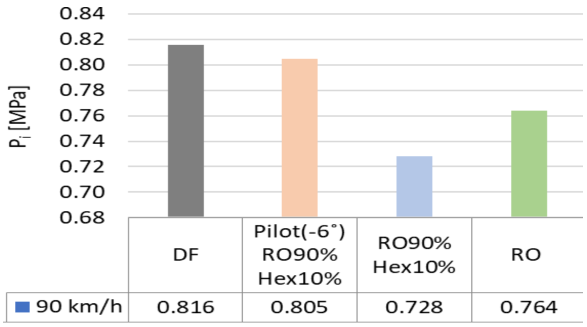

Fig. 7. Average indexed pressure, while running on a chassis dynamometer at 90 km/h, for selected fuels and control variant. The results were averaged from 100 engine cycles

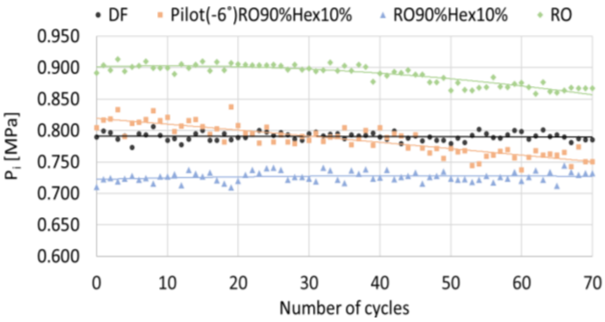

Fig. 8. The course of the average indexed pressure during driving on a chassis dynamometer at 90 km/h, for selected fuels and control variant depending on 70 engine cycles

In the case of feeding the engine with a mixture of rapeseed oil with 10% n-hexane additive and using an adjusted pilot injection start angle of –6°CA (Pilot(–6°)RO 90% Hex10%), the value of the average indexed pressure was 0.786 MPa. For the 70 engine cycles analyzed, it was most similar to diesel The value of maximum combustion pressure for Pilot(–6°)RO 90%Hex10% was 9.66 MPa. For the maximum pressure build-up rate (dp/dα), the measured value was 0.375 MPa/°CA. In terms of energy requirements, the average fuel burnup for this variant was 966.9 kJ/m³. The maximum heat rate (Qmax) reached 96.7 kJ/m³·°CA.

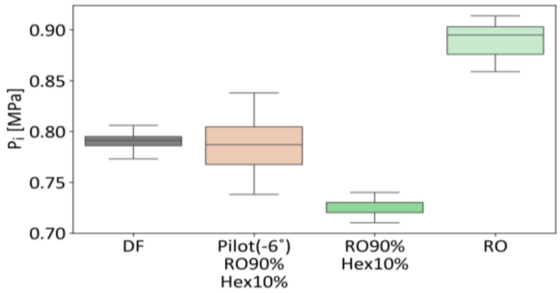

Fig. 9. Box plot showing a comparison of the distributions of mean indicated pressure measurements for the fuels tested for 70 engine cycles

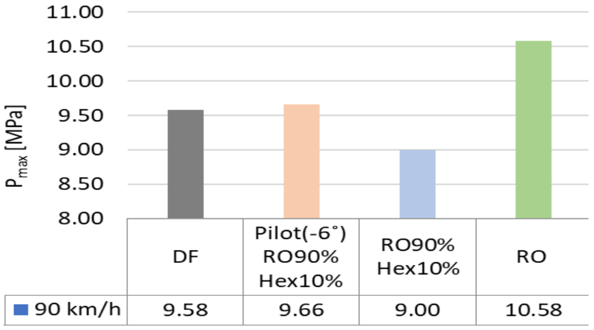

Fig. 10. Maximum combustion pressure during driving on a chassis dynamometer at 90 km/h, for selected fuels and control variant. The results were averaged from 100 engine cycles

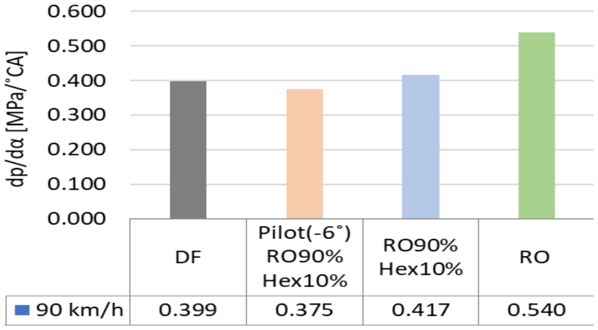

Fig. 11. The maximum speed of combustion pressure build-up, while running on a chassis dynamometer at 90 km/h, for selected fuels and control variant. The results were averaged from 100 engine cycles

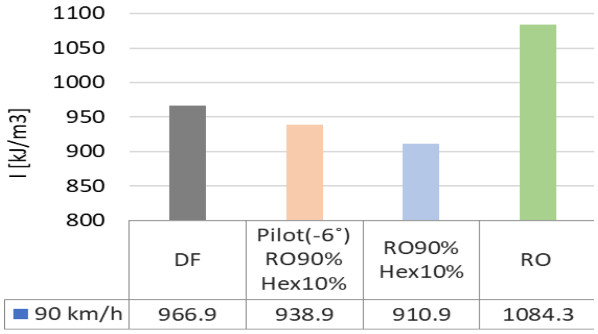

Fig. 12. The average amount of fuel burned, while running on a chassis dynamometer at 90 km/h, for selected fuels and control variant. The results were averaged from 100 engine cycles

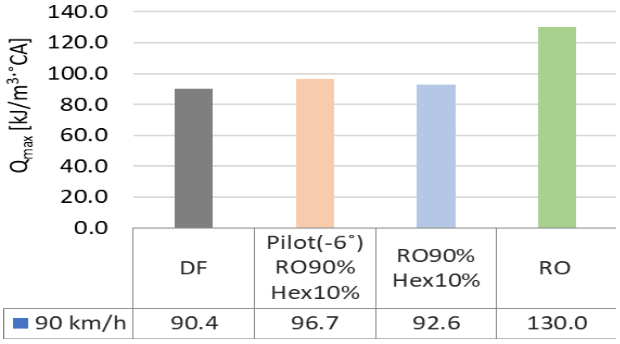

Fig. 13. The maximum rate of heat release, when running on a chassis dynamometer at 90 km/h, for selected fuels and control variant. The results were averaged from 100 engine cycles

4. Conclusions

The study shows that the use of an earlier start of pilot injection, shifted by –6°CA, when feeding the engine with a mixture of rapeseed oil with 10% n-hexane, improved the parameters of the combustion process and brought them closer, to the reference values obtained when burning diesel. It is worth noting that when fed with a mixture of RO 90%Hex10% without changing the injection angle, the average indexed pressure was 0.728 MPa, which is less than for diesel (DF = 0.816 MPa). The maximum combustion pressure, on the other hand, reached 9.00 MPa, which was the lowest of all the tested power variants. The reduced intensity of the combustion process was also confirmed by the course of the pressure build-up rate (dp/dα), which was 0.417 MPa/°CA, noticeably below the level for DF. Introducing a change in the pilot injection start angle by –6°CA brought significant benefits. The average indexed pressure increased to 0.805 MPa, reaching a level similar to DF. The maximum combustion pressure increased to a value of 9.66 MPa, which is virtually identical to DF (9.58 MPa). The course of pressure build-up: dp/dα was 0.375 MPa/°CA, below the level for diesel. The average fuel burn rate increased from 910.9 to 966.9 kJ/m³. Similarly, the maximum heat release rate was 96.7 kJ/m³·°CA, close to the value for diesel (90.4 kJ/m³·°CA). In conclusion, changing the pilot injection onset angle for the RO90%Hex10% mixture was a key procedure that made it possible to improve the ignition limits of the mixture used and achieve engine performance similar to that of diesel combustion. Improvements were achieved not only in combustion parameters but also in cyclic stability and combustion uniformity.

Nomenclature

CA	crank angle
CI	compression ignition
DF	diesel fuel
dp/dα	pressure build-up rate as a function of crankshaft rotation angle
dQ/dα	heat release rate as a function of crankshaft rotation angle
DI	direct injection
EGR	exhaust gas recirculation
NO_x	nitrogen oxides
OBD	on board diagnostics
P_c	cylinder pressure
$P_{c\ max}$	maximum cylinder pressure
Q_{max}	maximum heat release rate
RO	rapeseed oil
SOI	start of injection
TDC	top dead center
WLTP	Worldwide Harmonised Light Vehicles Test Procedure
$\alpha_{(inj)}$	injection angle
$\alpha_{Pc\ max}$	angle of rotation of the crankshaft at which there is maximum pressure in the cylinder

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